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DETERMINATION OF DENSITY AND CONCENTRATION FROM FLUORESCENT IMAGES OF A GAS FLOW

Applications to laboratory hypersonic jets

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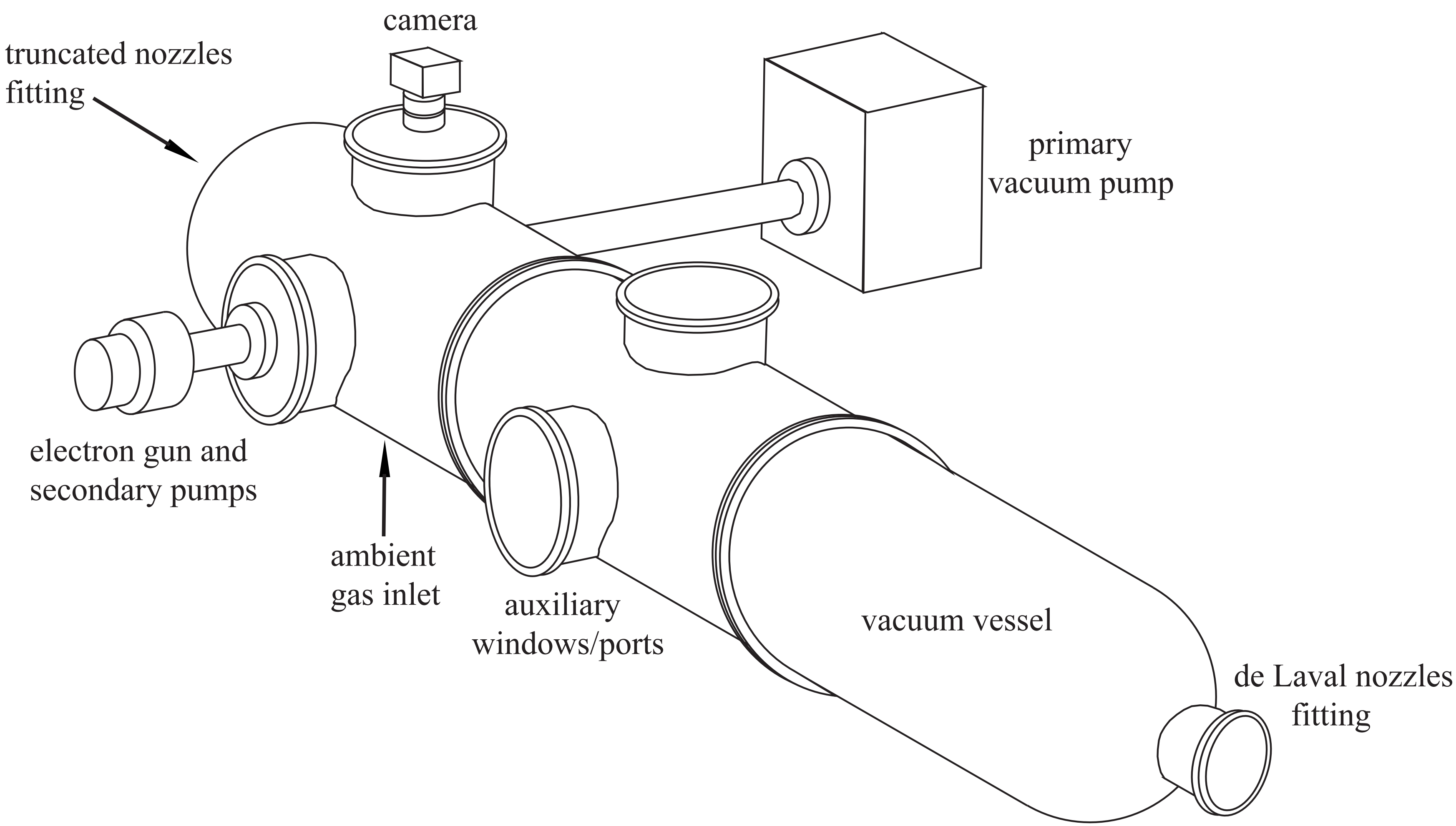
1 Facilities



•Vacuum vessel •Nozzles •Electron gun •High-sensitivity camera

2 Capability of the system / tested flows

(ICIASF meeting 2001, Astrophysics and Space Science 2004)

- Long-scale jet visualization (up to 100 initial diameters)
- 2D-visualizations of 3D-flows (slices)
- Density measurements
- Concentration measurements, jet gas $\neq$ environment gas
- Mixing layer thickness, shock thickness measurements

3 Physical conditions

- Rarefied gases ($n < 10^{22}\,\mathrm{m}^{-3}$, $p < 100\,\mathrm{Pa}$ and $\rho < 1\,\mathrm{g/m}^3$ for air)
- Stagnation/ambient pressure ratio: p_0/p_{amb} up to 10^5
- Mach number M up to 50 (or more, $v \sim v_{limit}$).
- Density ratio $0.04 < \rho_{\mathrm{jet}}/\rho_{\mathrm{amb}} < 45$ (0.01 to 100 is possible).
- Re_D up to 2000 (diameter), $Re_x > 10^5$ (axial length)

4 Density and concentration (mixing) measurements

4.1 *Fluorescent emission of rarefied gases*

Radiant intensity I vs numerical density n (Grün, 1954):

$$I = \frac{k_1\, n}{1 + \left(2\, n\, \sigma^2 {P_{ij}}^{-1} \sqrt{\frac{4\pi}{m} kT}\right)} = \frac{k_1\, n}{1 + k_2(T)\, n}$$

Typical fluorescent emission at constant T:

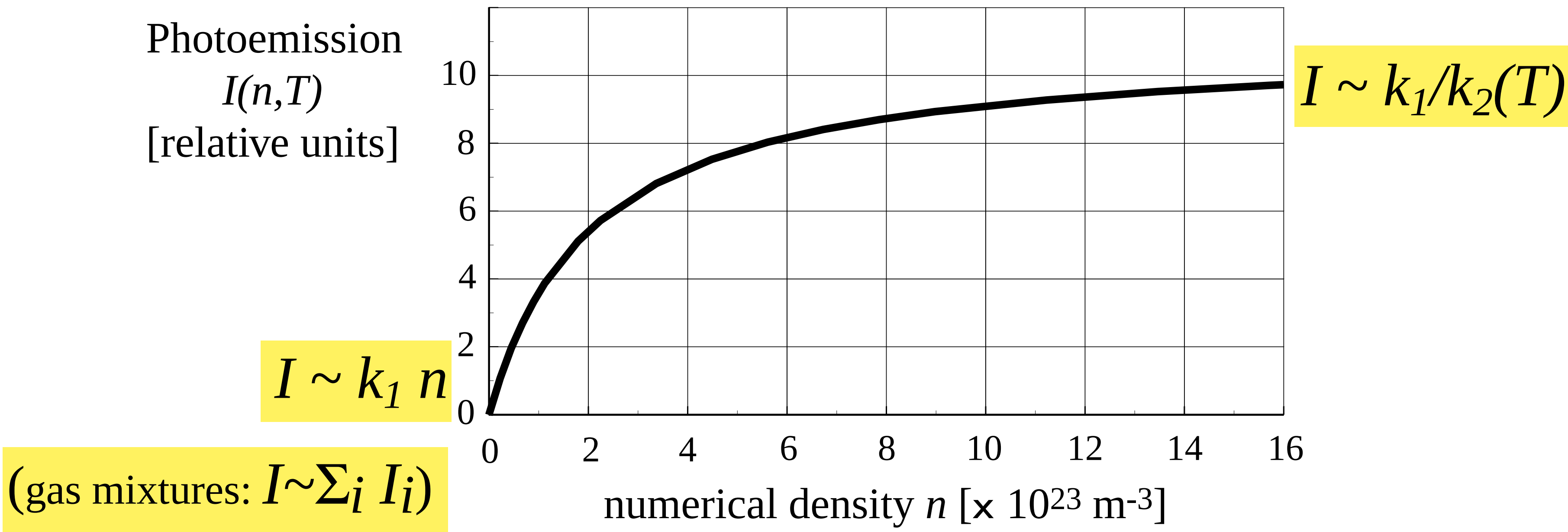
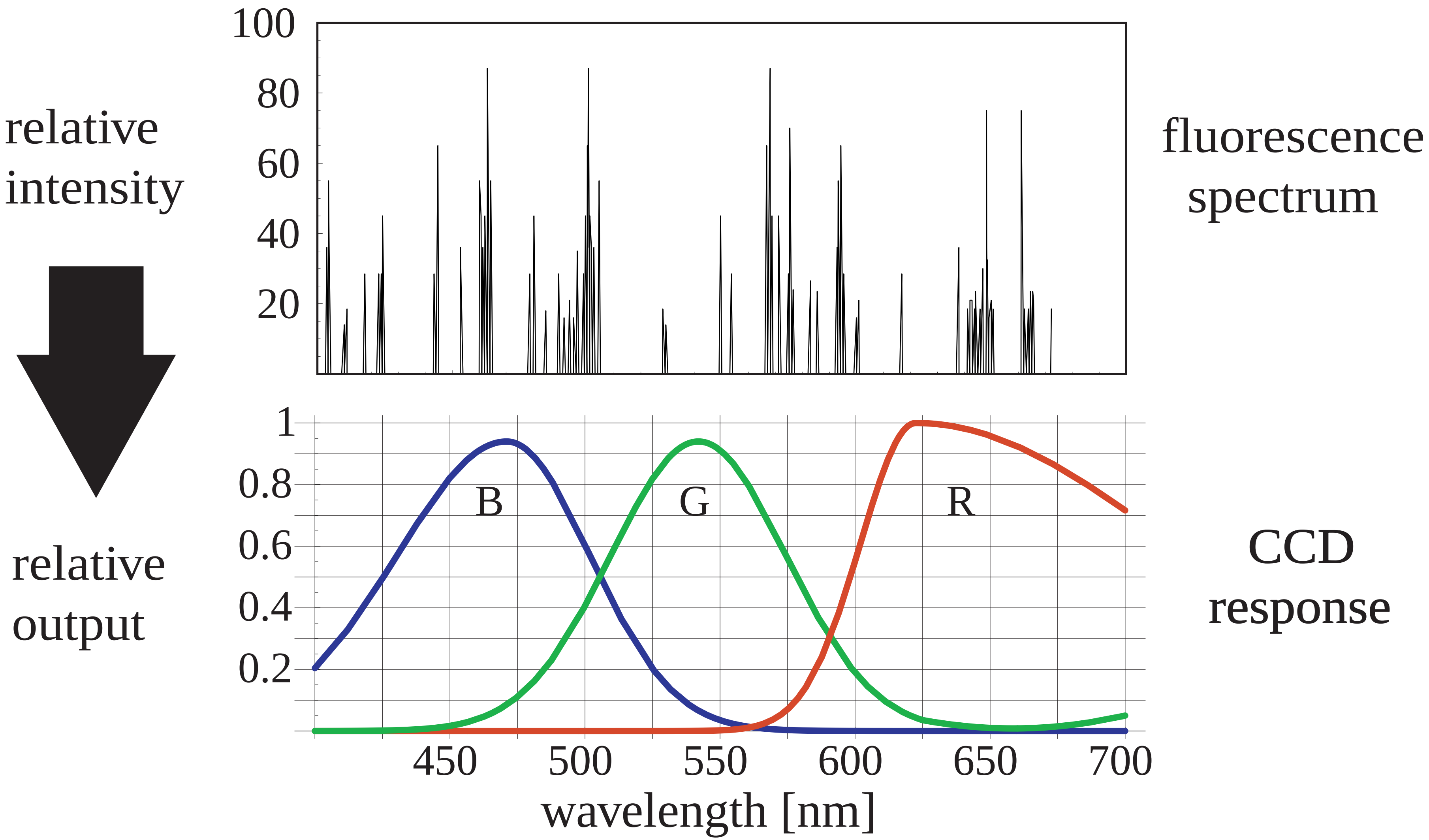


Image analysis: concentration



Algorithm: (Exp Fluids 2008)

$I = k\,n$ total emission $\propto$ numerical density n

$$\begin{cases} R = k_R\, n \\ G = k_G\, n \\ B = k_B\, n \end{cases} \qquad \text{CCD output colors (partial emission)} \propto n$$

$C = aR + bG + cB = k_C\, n$ weighted spectral superposition $\propto n$

For different gases:

$$\text{jet gas} \begin{cases} R_{\text{jet}} = k_{Rj} n_{\text{jet}} \\ G_{\text{jet}} = k_{Gj} n_{\text{jet}} \\ B_{\text{jet}} = k_{Bj} n_{\text{jet}} \end{cases} \qquad \text{ambient gas} \begin{cases} R_{\text{amb}} = k_{Ra} n_{\text{amb}} \\ G_{\text{amb}} = k_{Ga} n_{\text{amb}} \\ B_{\text{amb}} = k_{Ba} n_{\text{amb}} \end{cases}$$

Example: He jet in Ar ambient ($I_{He} < I_{Ar}$).

Decoupled emission gives $R = R_{He} + R_{Ar}$, $G = G_{He} + G_{Ar}$

$$\Longrightarrow r_{\text{pure Ar}} \le \frac{G}{R} \le r_{\text{pure He}}$$

In general, for a mixture of 2 gases,

$$r_{\min} \le \frac{C_1}{C_2} \equiv \frac{a_1R + b_1G + c_1B}{a_2R + b_2G + c_2B} \le r_{\max}$$

Decoupled emission for a given color combination C:

$$\boxed{C_{\text{mix}} = C_{\text{amb}} + C_{\text{jet}}}$$
$$k_C\, n = k_{\text{a}} n_{\text{amb}} + k_{\text{j}} n_{\text{jet}}$$

Introducing $z_{\text{gas}} = n_{\text{gas}}/n$:

$$k_C = k_{\text{a}} z_{\text{amb}} + k_{\text{j}} z_{\text{jet}} = k_{\text{a}}(1 - z_{\text{jet}}) + k_{\text{jet}} z_{\text{jet}}$$

Color combinations setup (choice of $a_1, b_1, c_1,\ a_2, b_2, c_2$):

$$C_1 = a_1 R + b_1 G + c_1 B \quad ; \quad C_2 = a_2 R + b_2 G + c_2 B$$

Definition of the color ratio:

$$r \equiv \frac{C_1}{C_2} = \frac{k_{C1}}{k_{C2}} = \frac{k_{\text{a}1} z_{\text{amb}} + k_{\text{j}1} z_{\text{jet}}}{k_{\text{a}2} z_{\text{amb}} + k_{\text{j}2} z_{\text{jet}}}$$

Concentration (solving for z_{jet}):

$$\boxed{z_{\text{jet}}(r) = \frac{k_{\text{a}1} - k_{\text{a}2}\, r}{\left(k_{\text{a}1} - k_{\text{j}1}\right) + \left(k_{\text{j}2} - k_{\text{a}2}\right) r}}$$

(k-constants are obtained by experimental calibration)

4.3 *Image analysis: density*

Radiant intensity of gases (decoupled emissions):

$$I_{\text{jet}} = k_{\text{j}}\, n_{\text{jet}}$$
$$I_{\text{amb}} = k_{\text{a}}\, n_{\text{amb}}$$

Radiant intensity of the gas mixture gives the total numerical density:

$$I = I_{\text{jet}} + I_{\text{amb}} = (k_{\text{j}}\, z_{\text{jet}} + k_{\text{a}}\, z_{\text{amb}})n$$
$$\Longrightarrow n = I/(k_{\text{j}}\, z_{\text{jet}} + k_{\text{a}}\, z_{\text{amb}})$$

Density (m: molar masses):

$$\rho = n(z_{\text{amb}} m_{\text{amb}} + z_{\text{jet}} m_{\text{jet}})$$

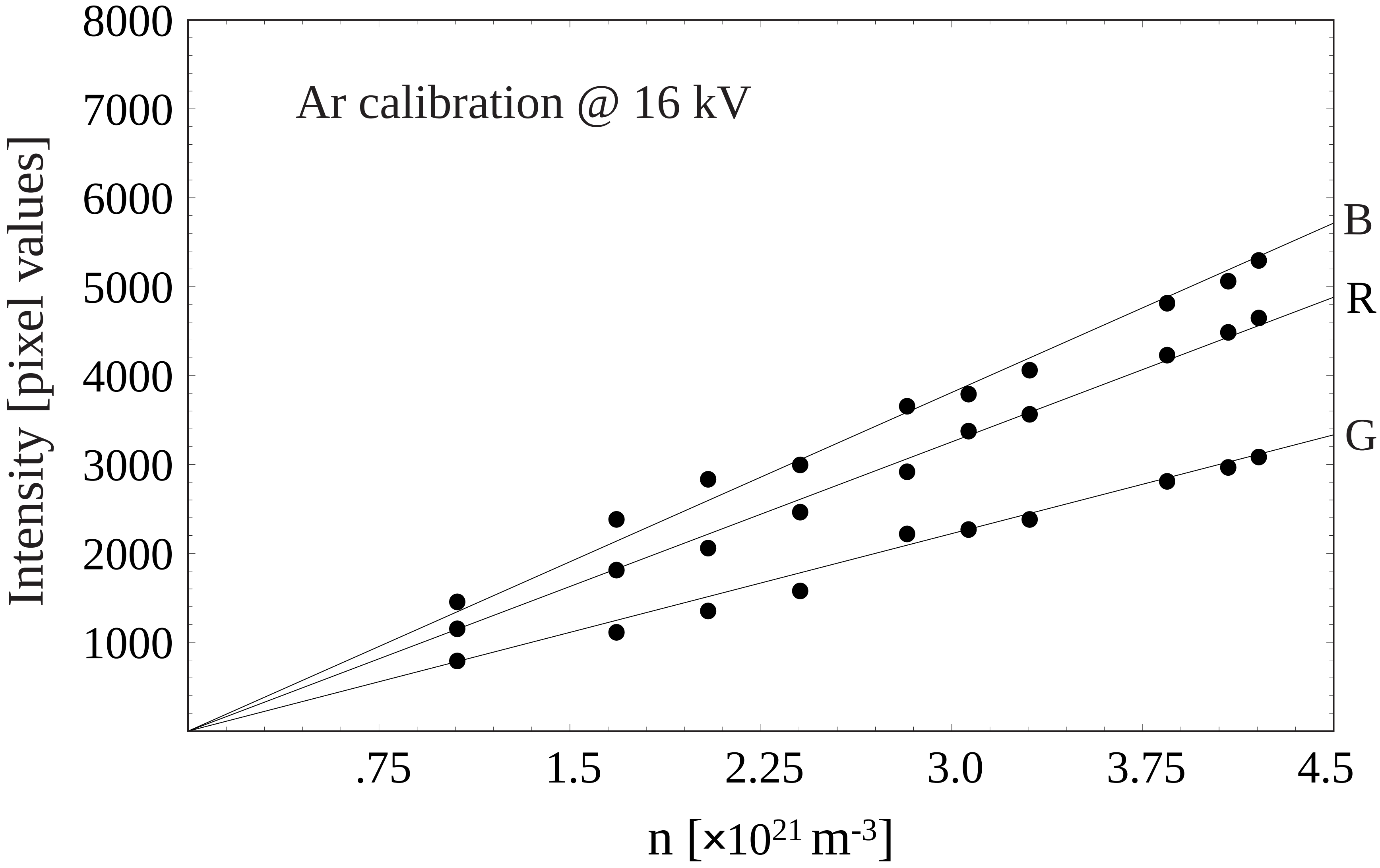
Remarks:

On the image domain $r(x,y) \mapsto z_{\text{jet}}(x,y), z_{\text{amb}}(x,y) \mapsto \rho_{\text{mix}}(x,y)$

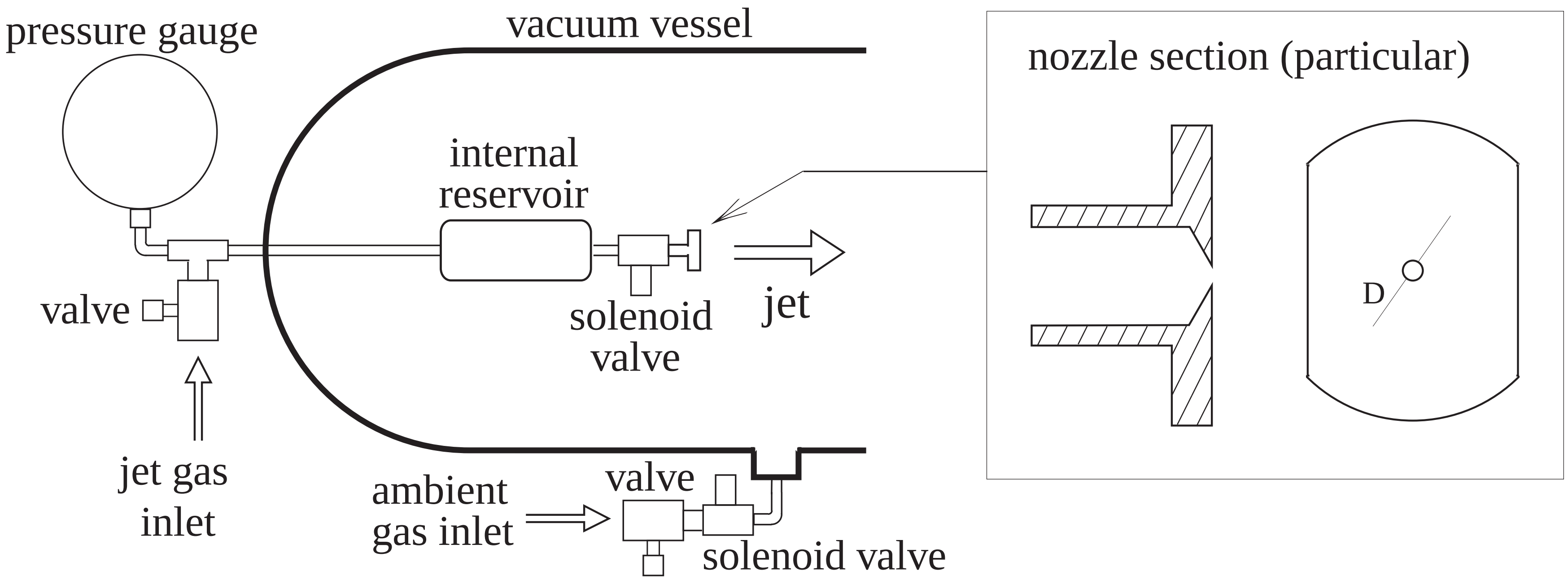
- C_1, C_2 should be chosen to get the widest range for $r = C_1/C_2$
- results may be strongly noise-sensitive
- if (jet gas)=(ambient gas) the density is much easier to calculate

4.4 *Calibration (example)*

(* 2008)



5 Underexpanded jets

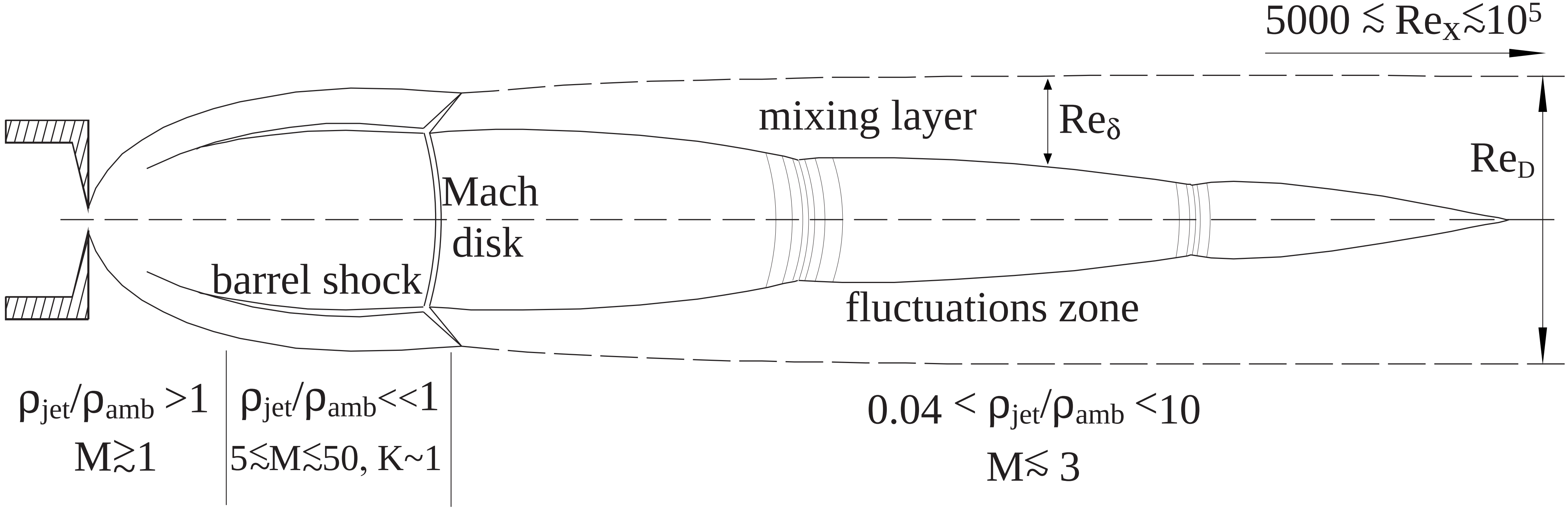


- Small jet radius: $r_{jet} < 0.1\, r_{vessel}$
- Quasi-stationary jet: $\Delta t_{valve} \gg t_{jet}$

Adjustable parameters:

- (stagnation/ambient) pressure ratio p_0/p_{amb}: $M_{\max} = f(p_0/p_{\mathrm{amb}})$
- density ratio $\rho_{\mathrm{jet}}/\rho_{\mathrm{amb}}$ (selection of light or heavy gases)

Jet structure:



Jets similarity:

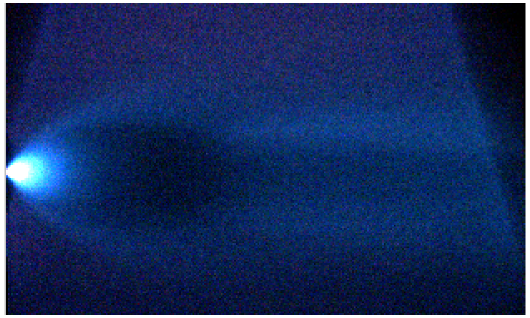
- Short range (barrel zone): $\rho_{\rm jet}/\rho_{\rm amb}$ similarity, (the jet properties depend on the pressure ratio $p_0/p_{\rm \ amb}$)
- Long range: Mach similarity, (the jet properties depend on the density ratio $\rho_{\rm jet}/\rho_{\rm amb}$)

6 Results

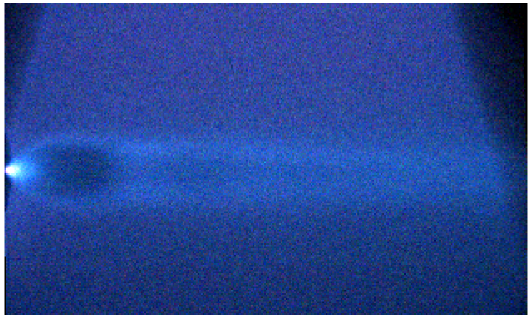
Example: Argon jet in Helium medium

7 Results

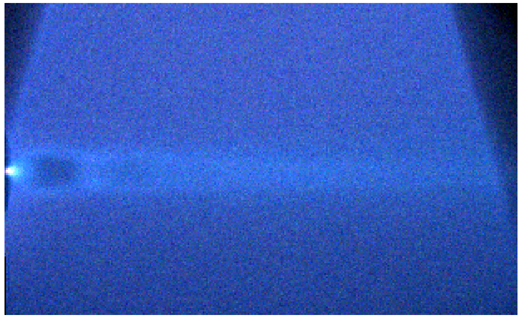
Helium jets in Argon medium: jets at several pressure ratios $p_0/p_{\,\mathrm{amb}}$



$M_{\mathrm{max}} \simeq 36$

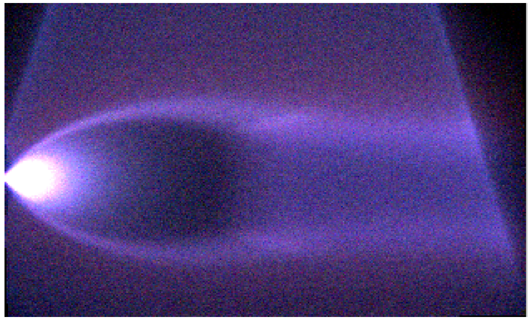


$M_{\mathrm{max}} \simeq 25$

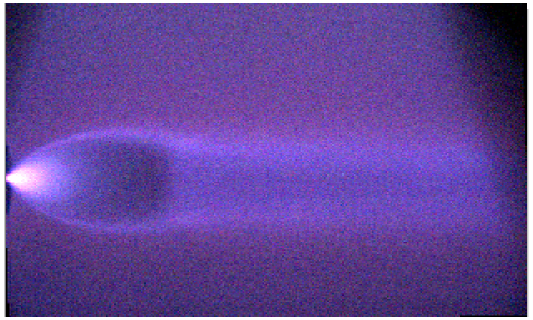


$M_{\mathrm{max}} \simeq 17$

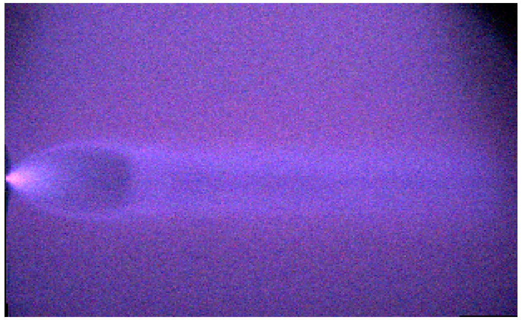
Argon jets in Helium medium: jets at several pressure ratios $p_0/p_{\,\mathrm{amb}}$



$M_{\mathrm{max}} \simeq 36$



$M_{\mathrm{max}} \simeq 29$

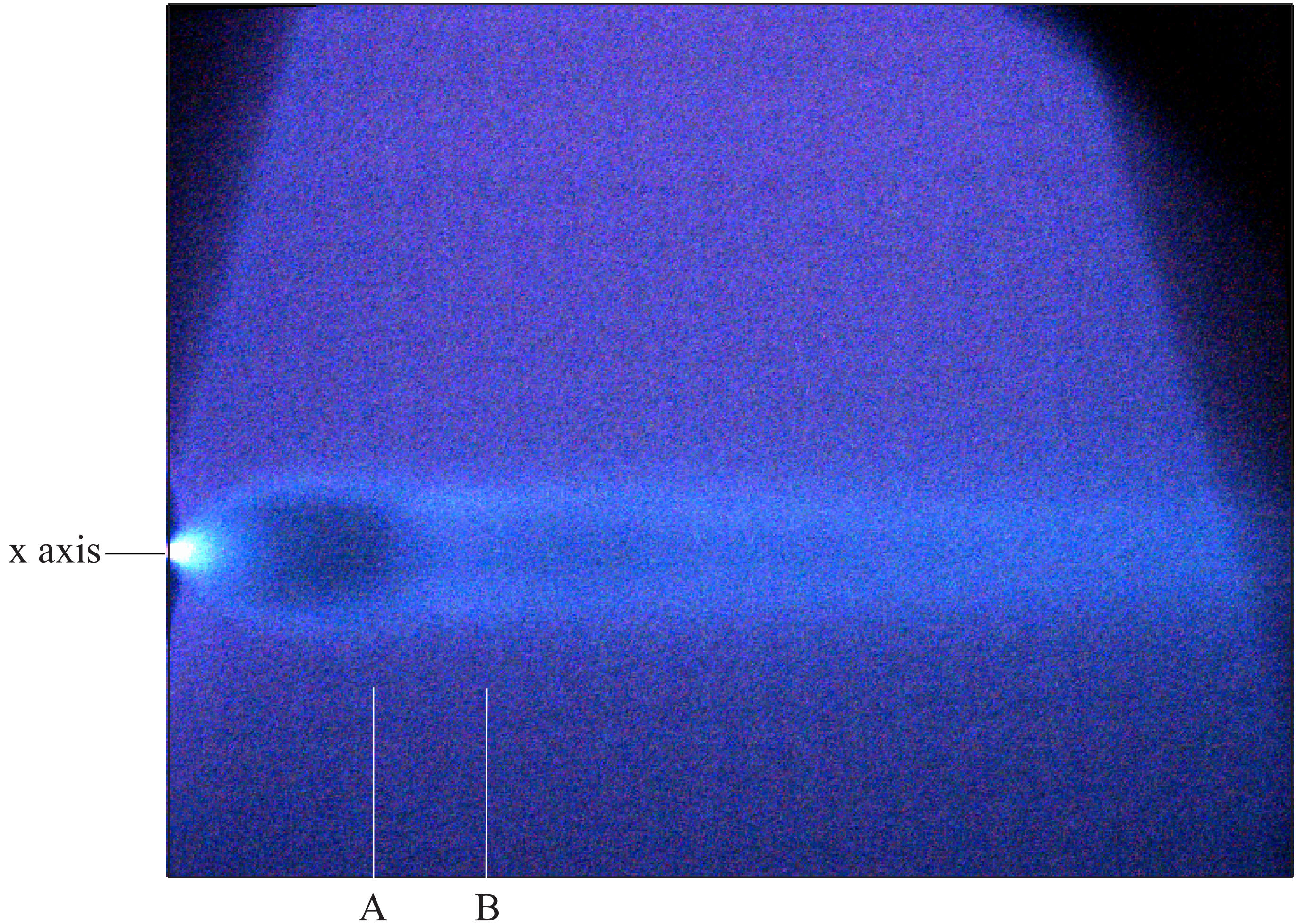


$M_{\mathrm{max}} \simeq 25$

(other gases in use: air, xenon)

7.1 *Light jet in heavy medium, same γ (monoatomic gases)*

Example: Helium jet in Argon medium.

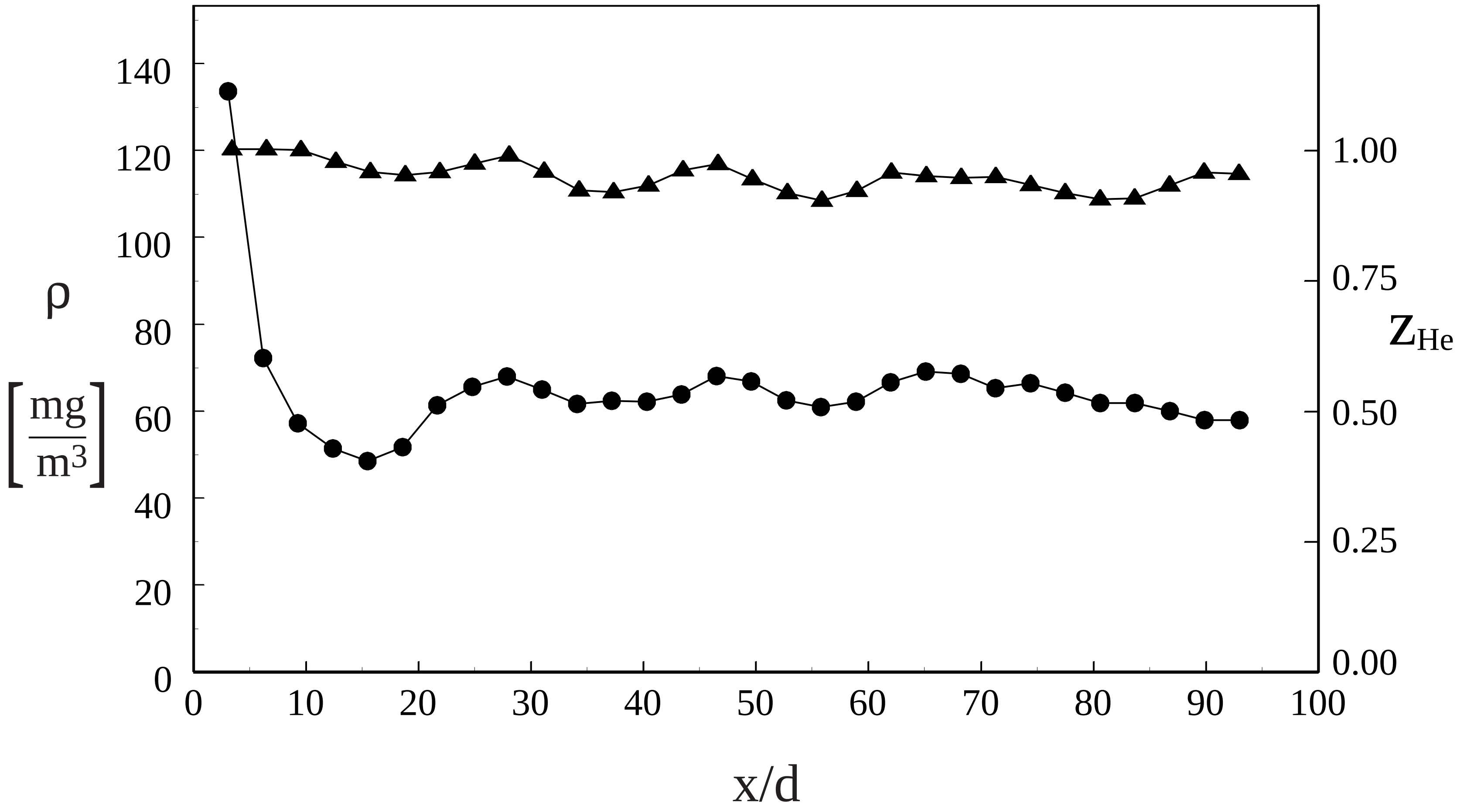


unbalanced RGB image, long exposure time (80ms $\gg$ time scale)

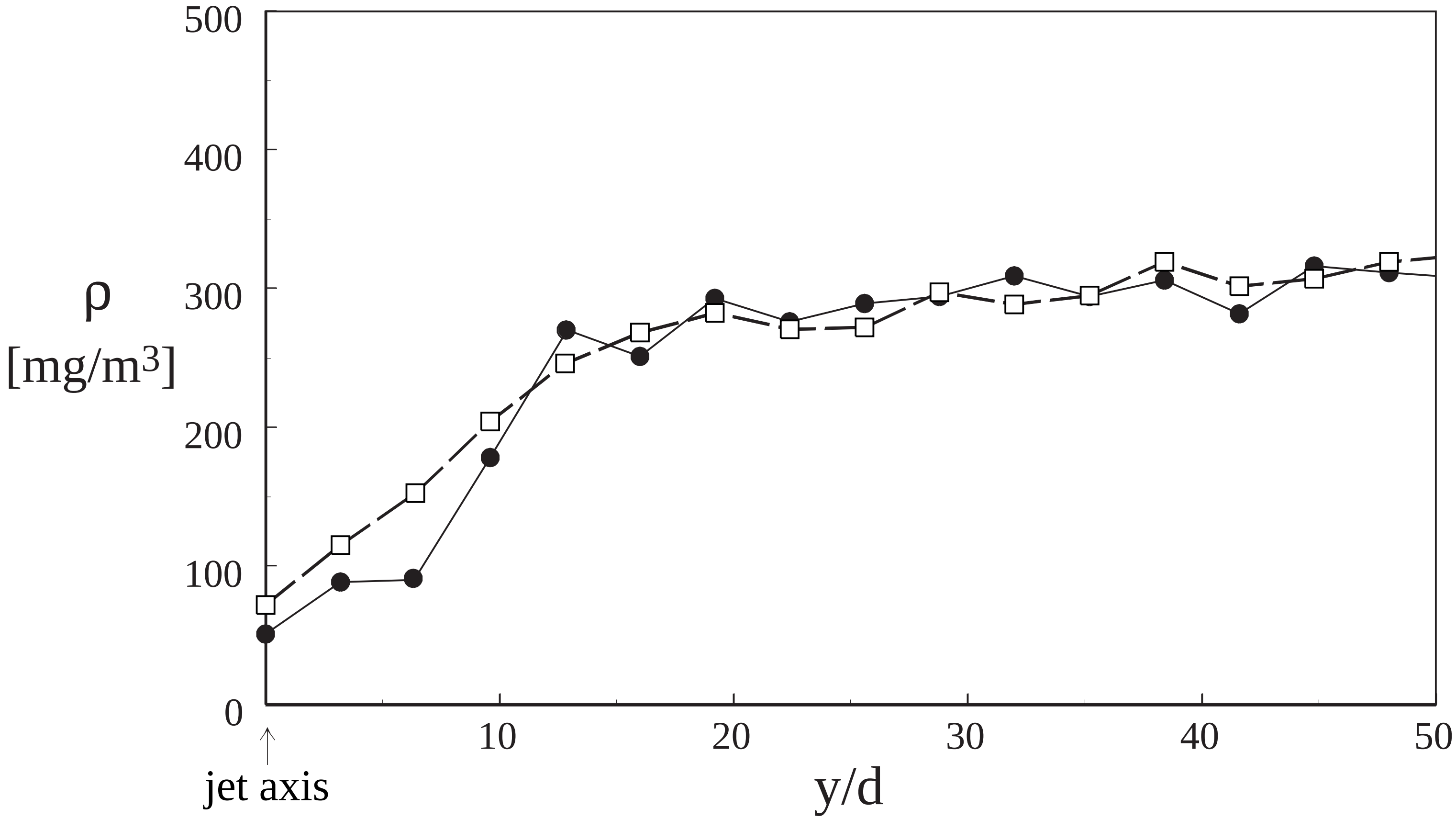
$$p_0/p_{\,\mathrm{amb}} \simeq 840 \ ; \ M_{\mathrm{max}} \simeq 26 \ ; \ \rho_{\,\mathrm{jet}}/\rho_{\,\mathrm{amb}} \simeq 0.14$$

weak gradients, density/pressure fluctuations after the shock

Helium jet in argon medium: axial density and concentration

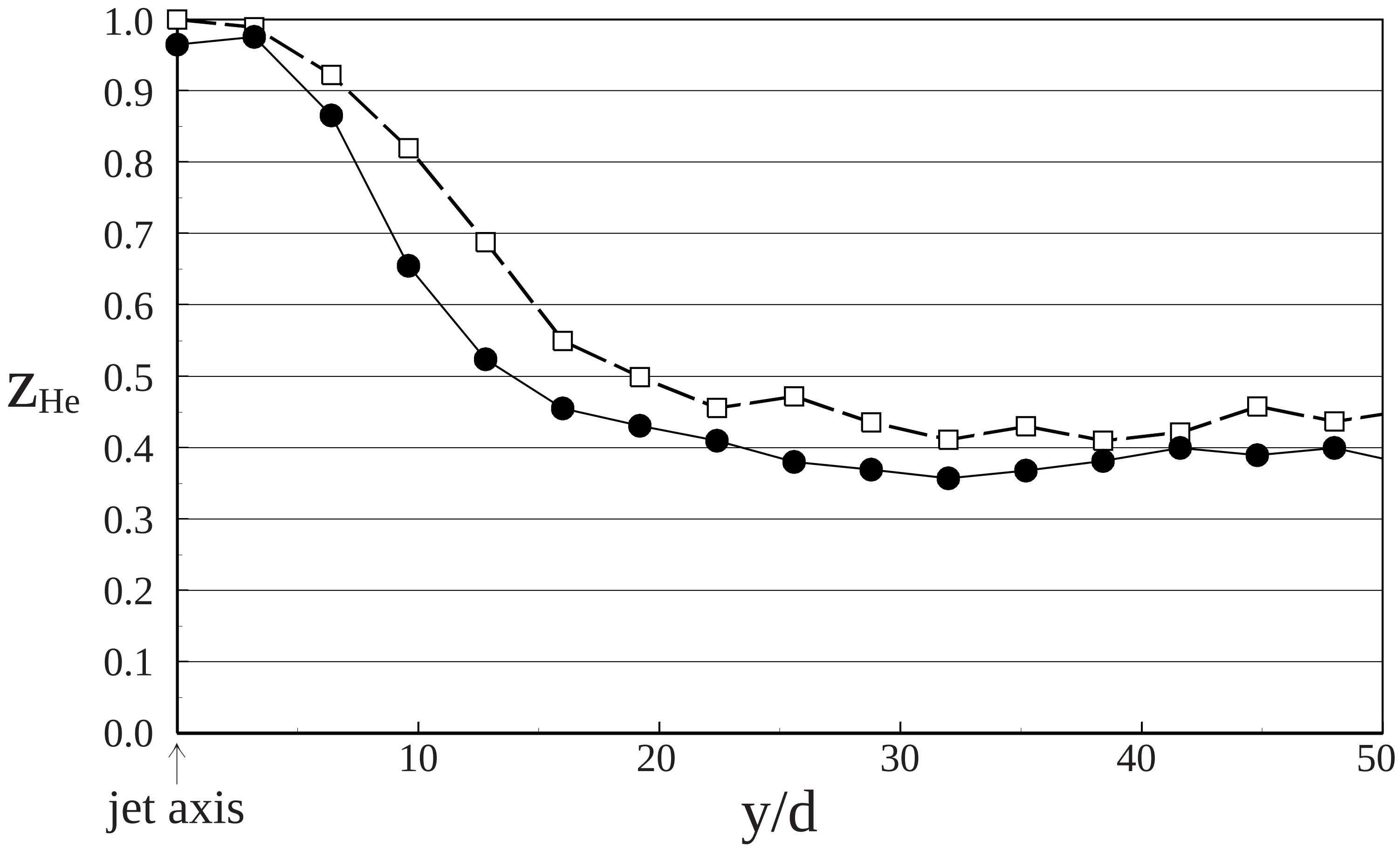


Helium jet in argon medium: radial density



●: section (A), before the Mach disk. □: section (B), after the Mach disk.

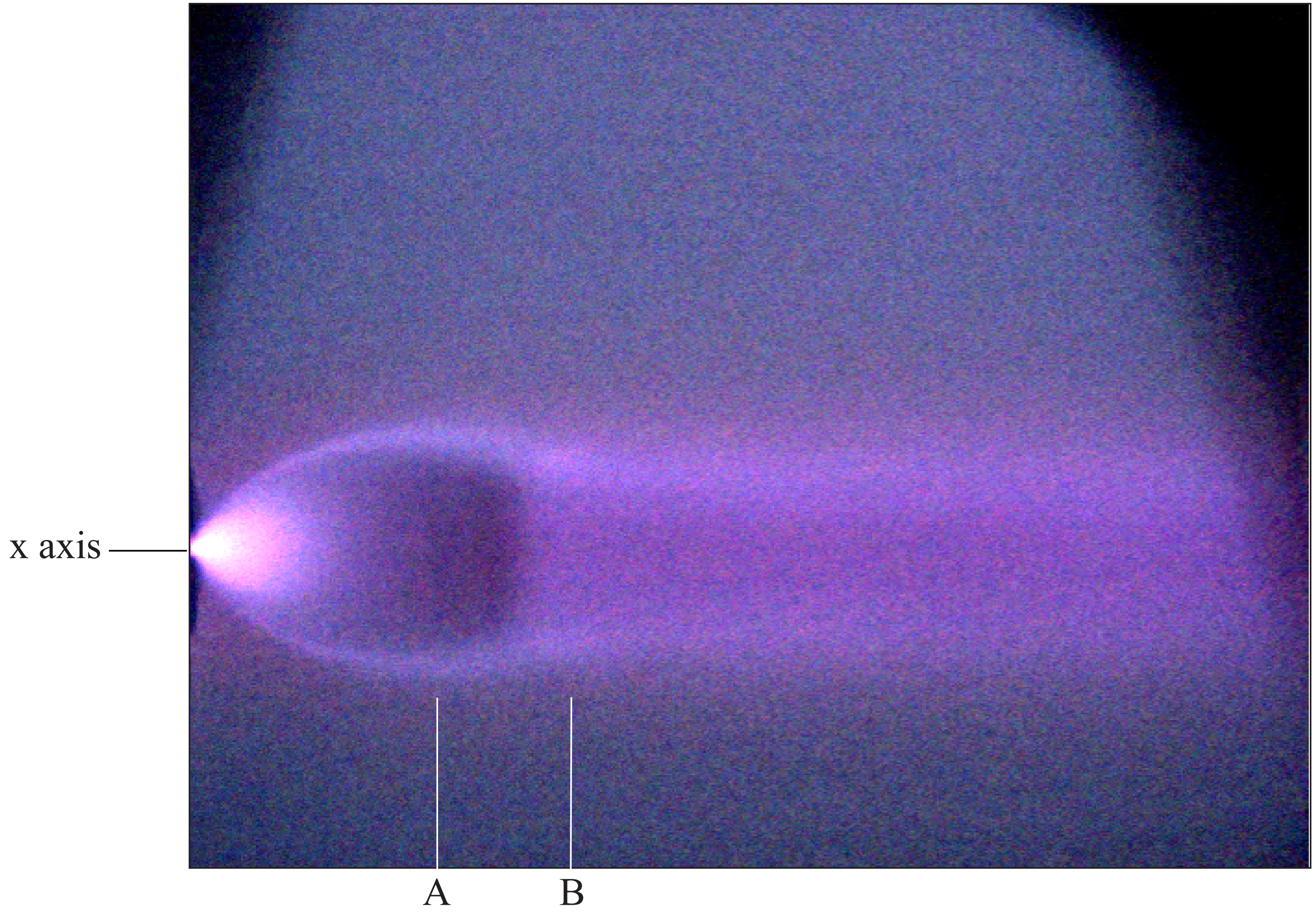
Helium jet in argon medium: radial concentration



●: section (A), before the Mach disk. □: section (B), after the Mach disk.

7.2 *Heavy jets in light mediums, same γ (monoatomic gases)*

Example: Argon jet in Helium medium.

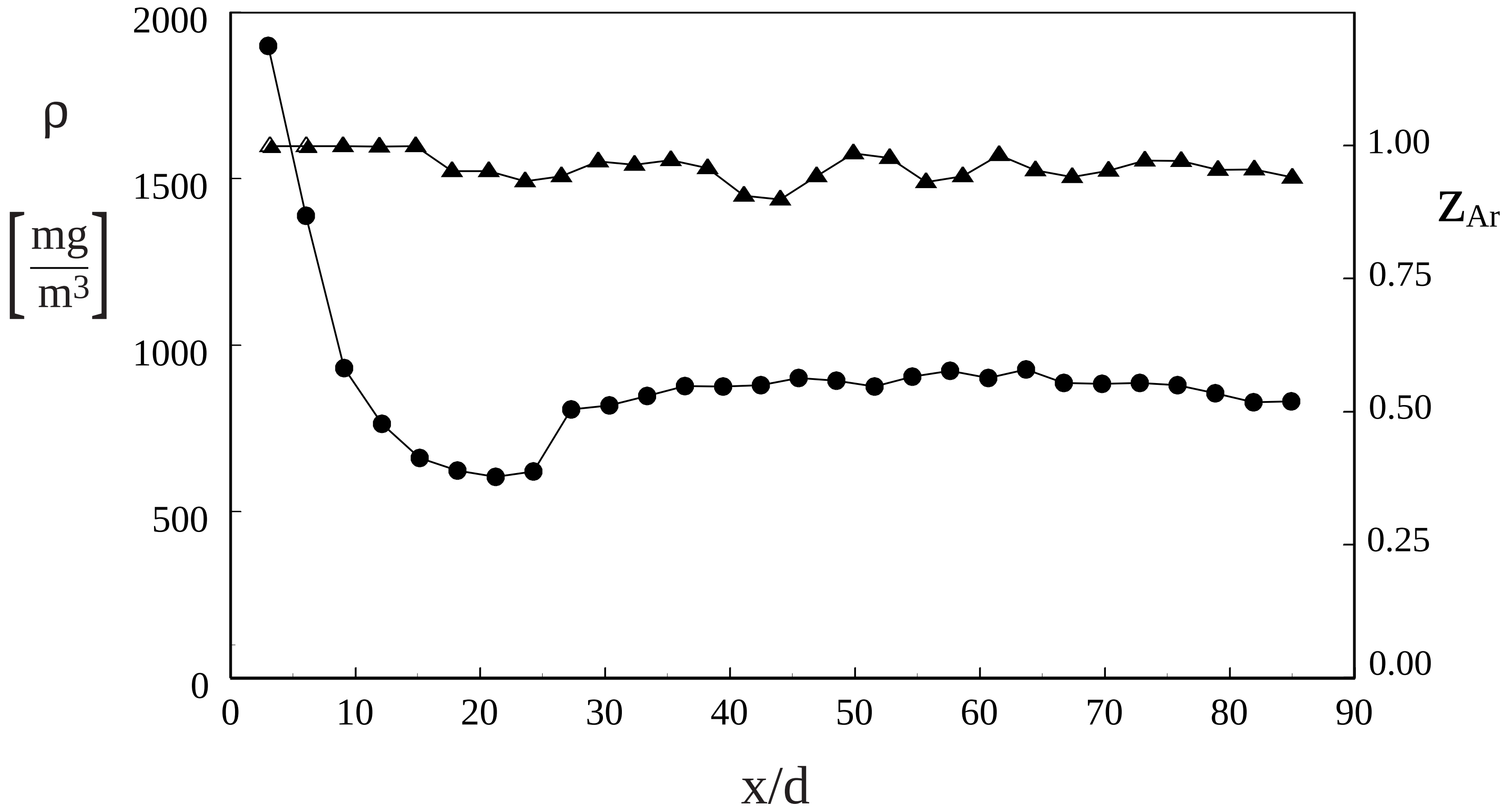


unbalanced RGB image, long exposure time (80ms $\gg$ time scale)

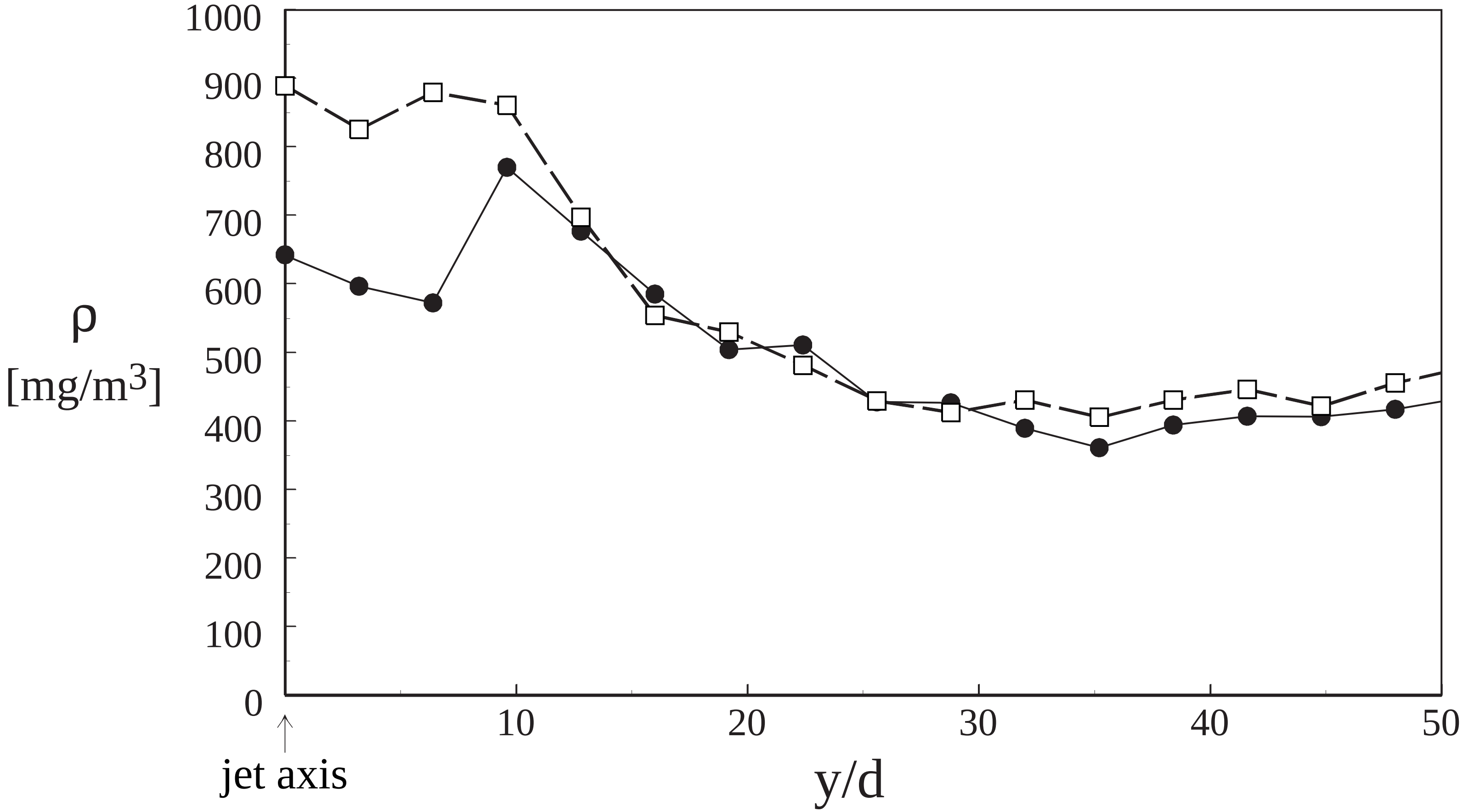
$$p_0/p_{\text{amb}} \simeq 1200\ ;\ M_{\max} = 29\ ;\ \rho_{\text{jet}}/\rho_{\text{amb}} \simeq 11$$

sharp gradients, no fluctuations after the normal shock

Argon jet in helium medium: axial density and concentration

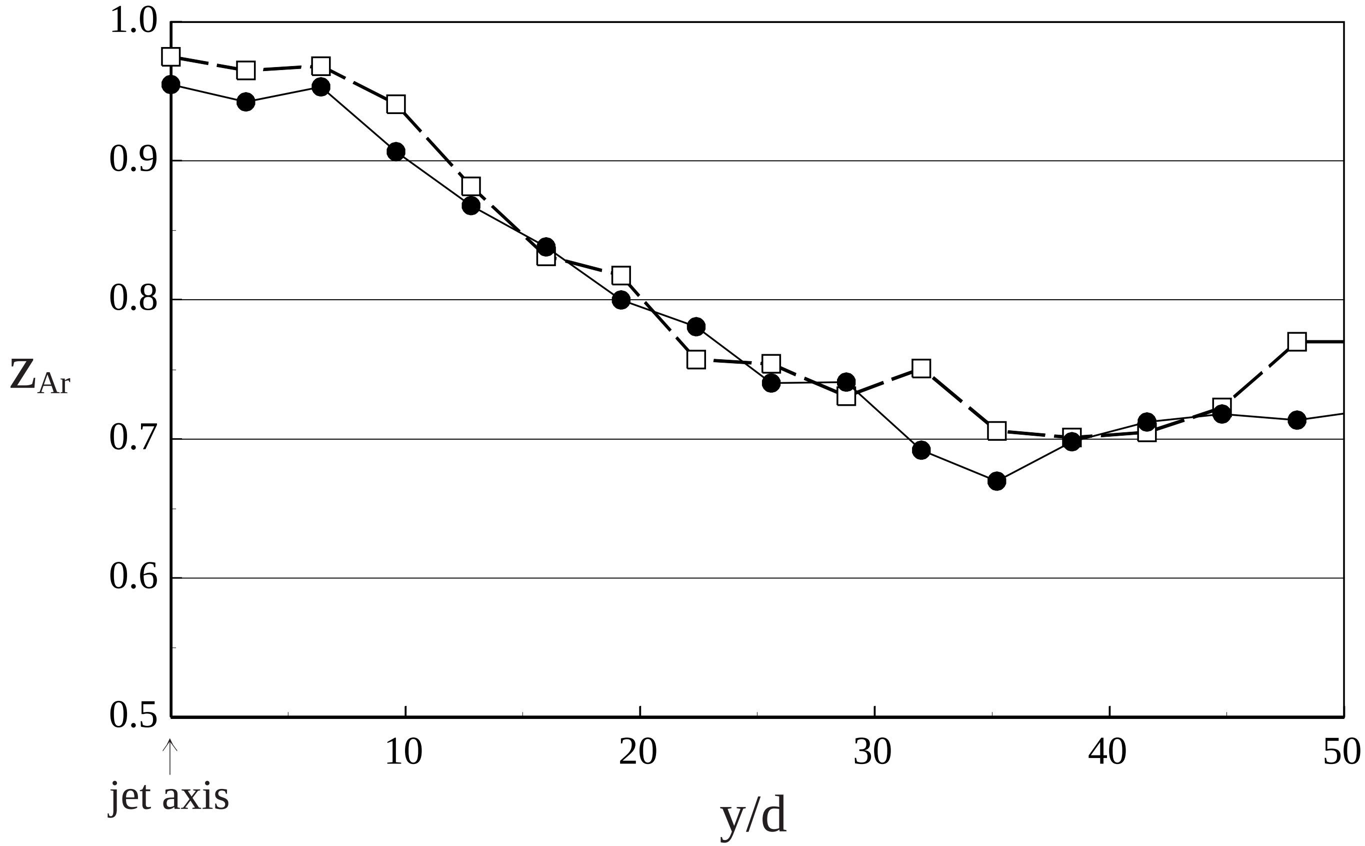


Argon jet in helium medium: radial density



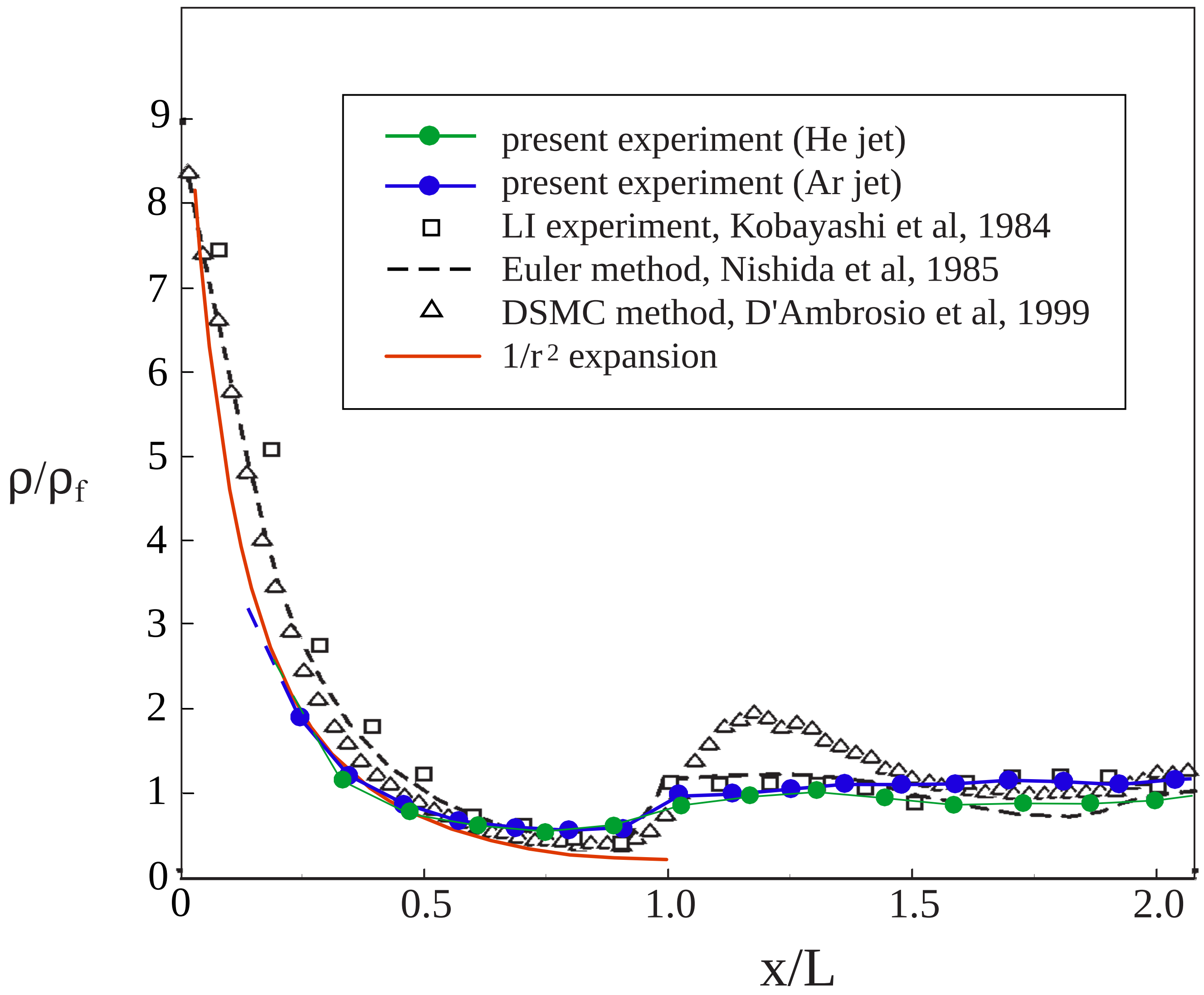
●: section (A), before the Mach disk. □: section (B), after the Mach disk.

Argon jet in helium medium: radial concentration



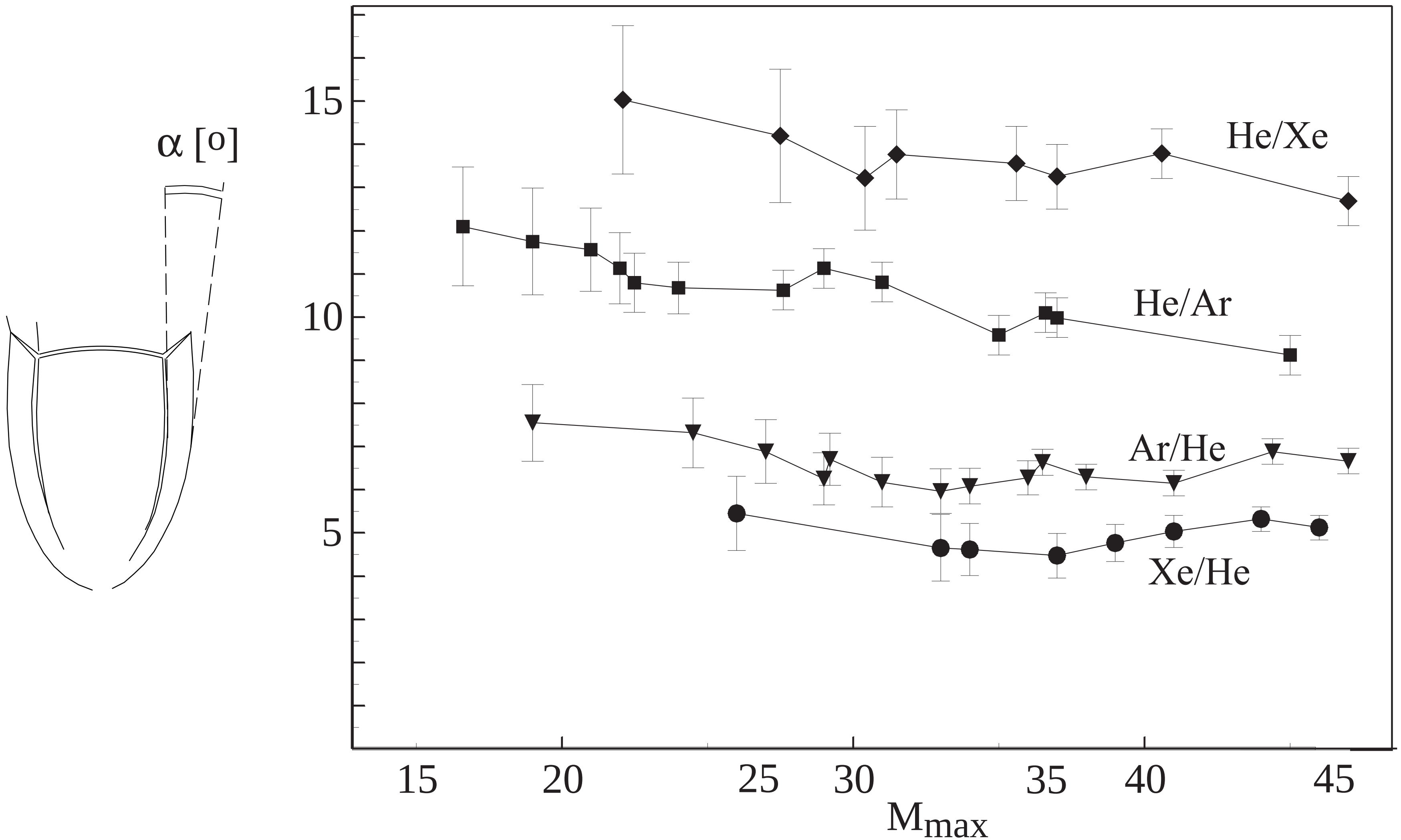
●: section (A), before the Mach disk. □: section (B), after the Mach disk.

7.3 *Comparison with literature data*



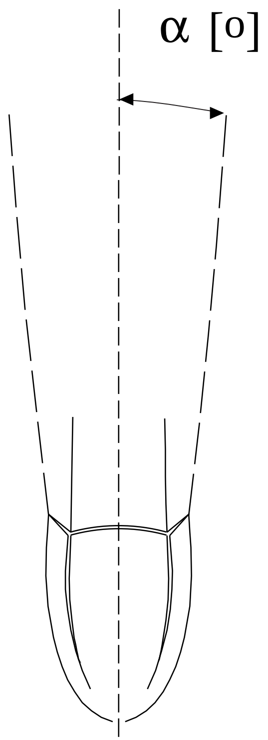
 z-measurements: collected data

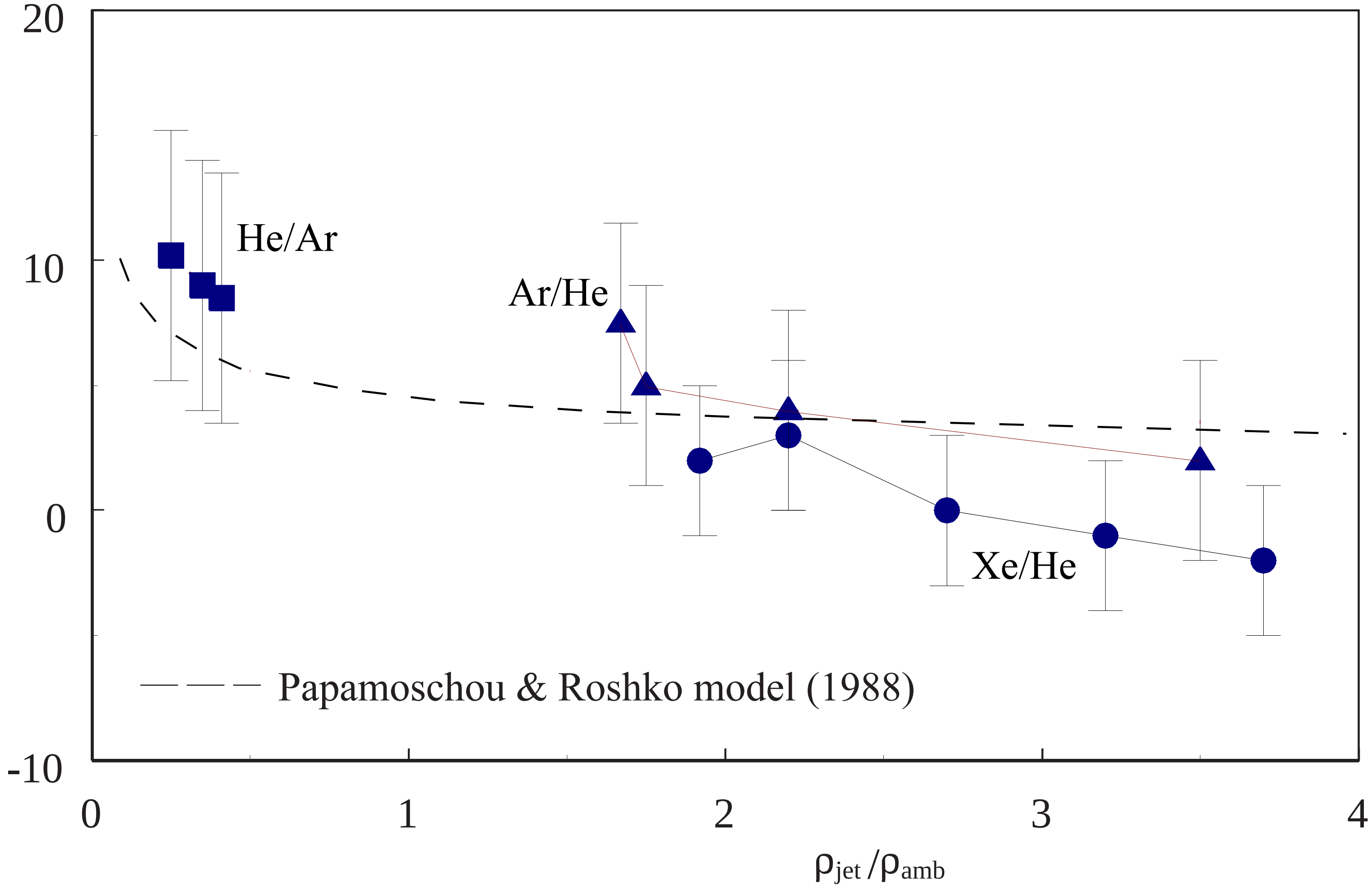
Near jet: Mixing layer (plume) spreading angle α vs M_{max}. (* 2008)



Barrel zone, before the Mach disk. Cross-section at $x = 0.8$ barrel lengths

Far jet: jet spreading angle α vs ρ_{jet}/ρ_{amb} (* 2007, unpublished [Msc thesis])



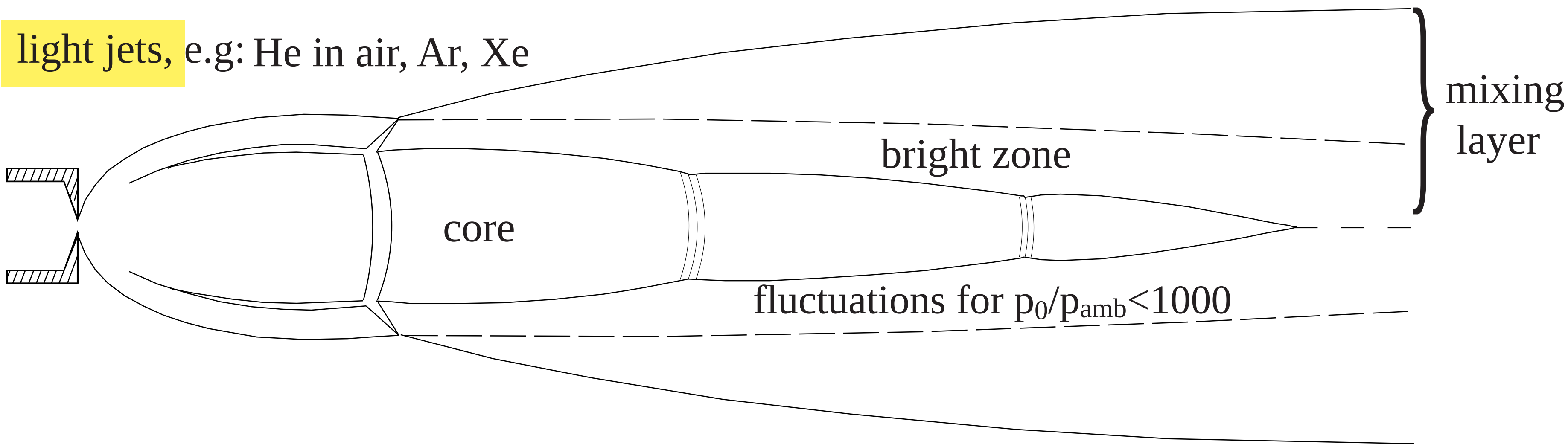


long range, Cross-section at 2.5 barrel lengths

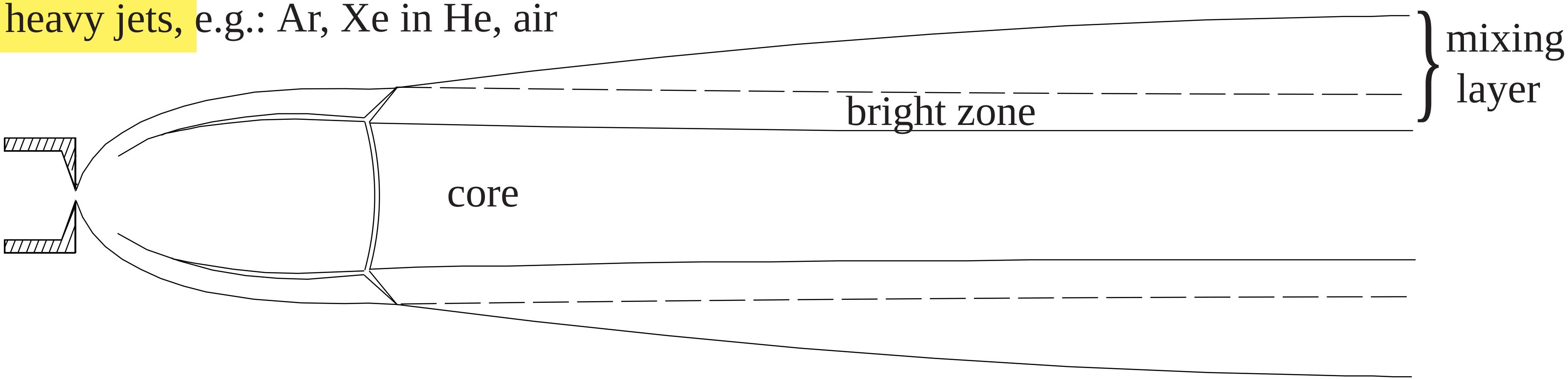
8 Underexpanded jet: results outline

Jet morphology in the range $500 < p_0/p_{\mathrm{amb}} < 10^5$, $0.1 < \rho_{\mathrm{jet}}/\rho_{\mathrm{amb}} < 15$

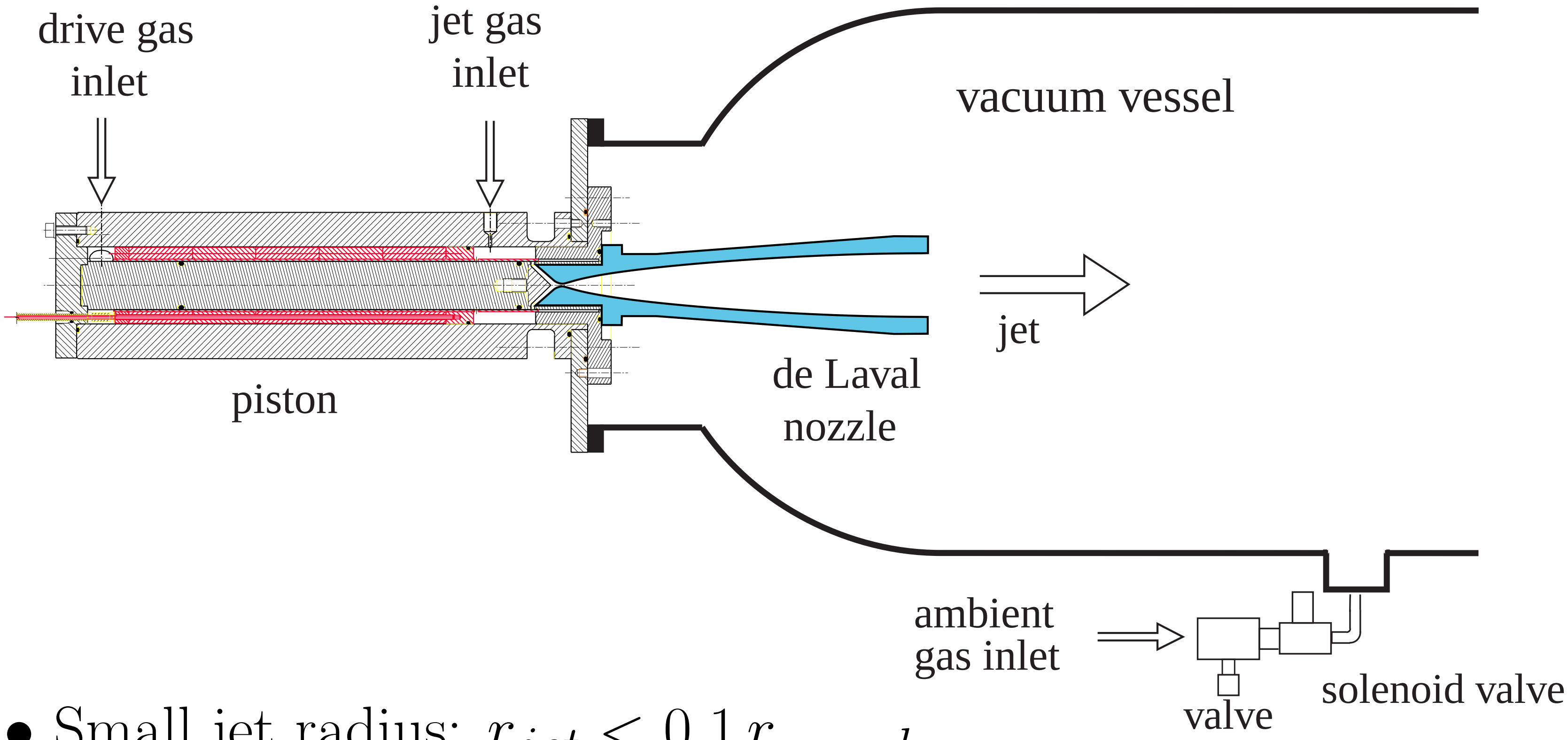
light jets, e.g: He in air, Ar, Xe



heavy jets, e.g.: Ar, Xe in He, air



9 Isoentropic jets

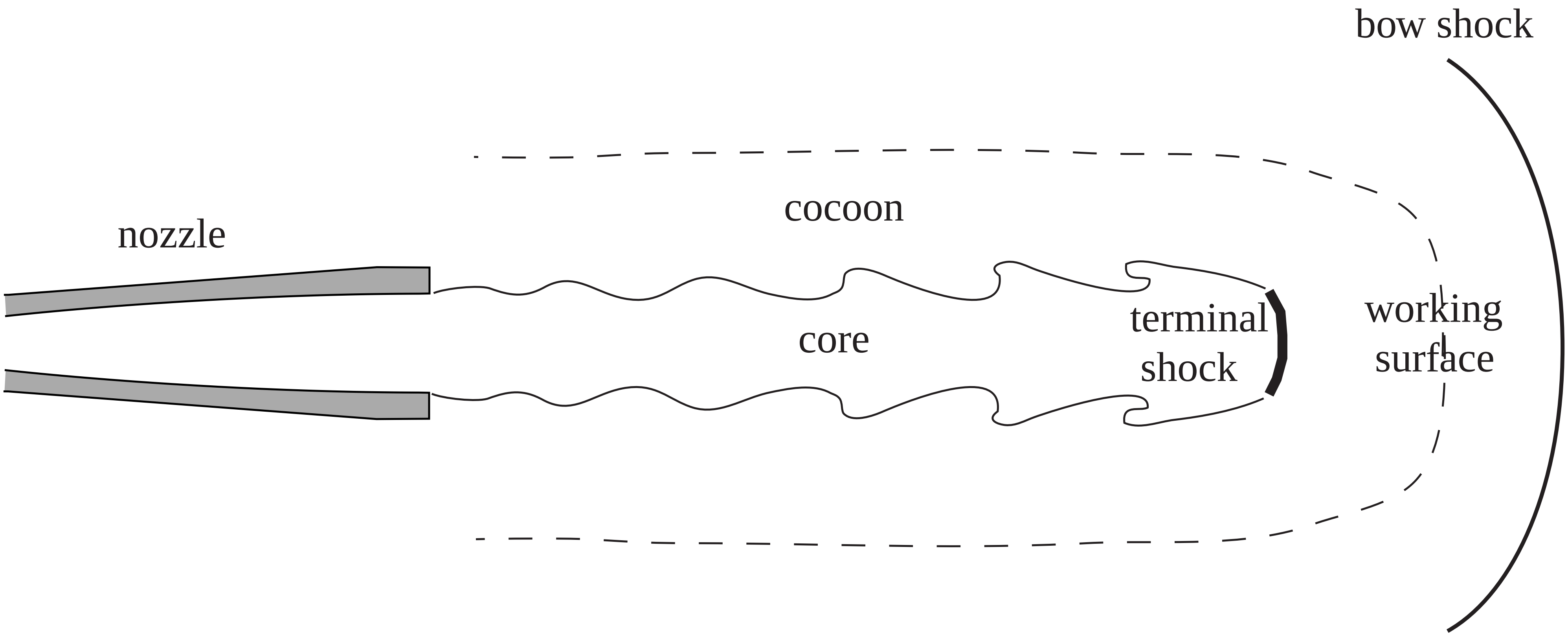


- Small jet radius: $r_{jet} < 0.1\, r_{vessel}$
- Fast (single pulse) jets: $\Delta t_{piston} \simeq t_{jet}$

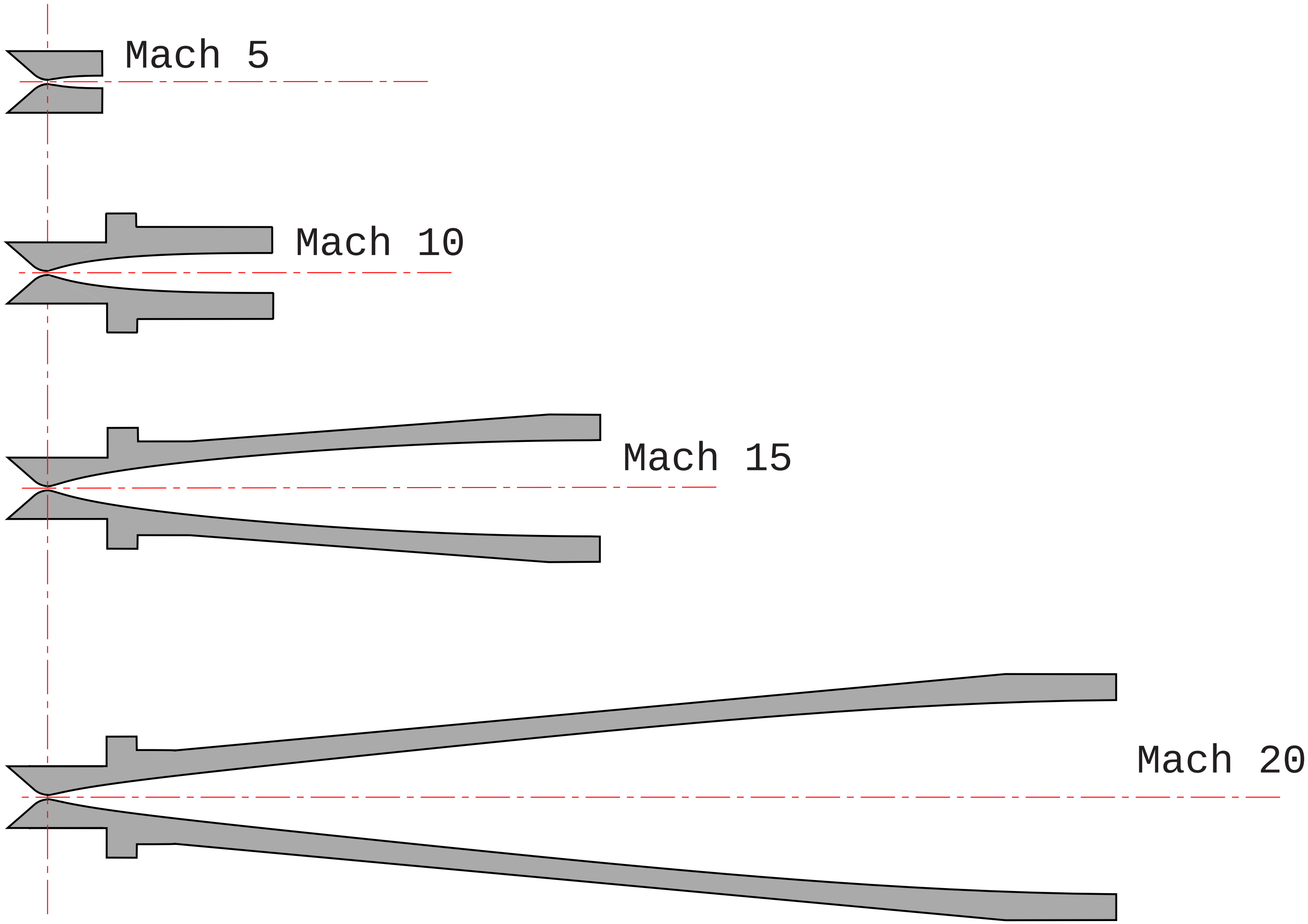
Adjustable parameters:

- jet Mach number M_{jet}
- density ratio $\rho_{\text{jet}}/\rho_{\text{amb}}$ (selection of light or heavy gases)

Expected jet structure:

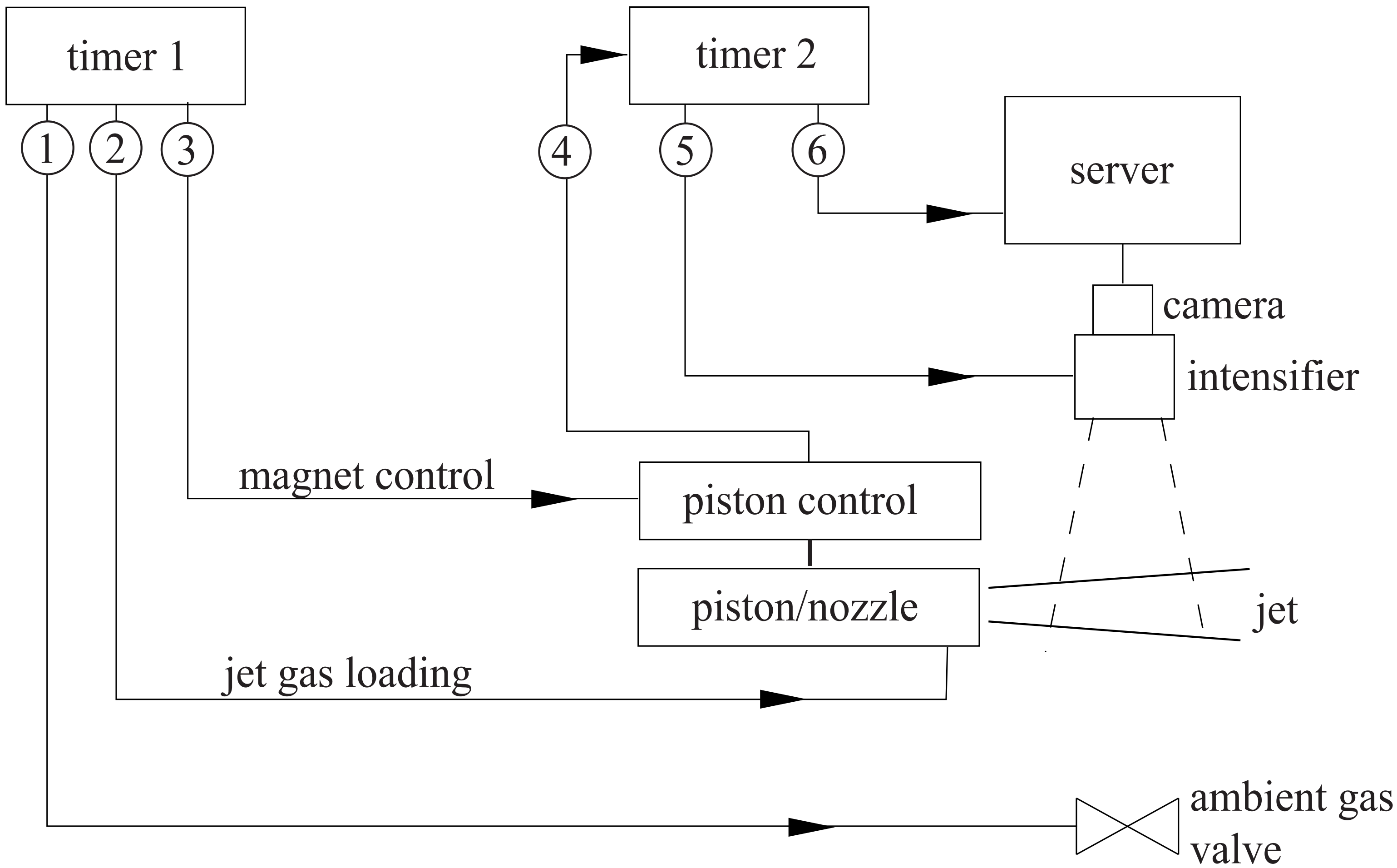


Interchangeable de Laval nozzles

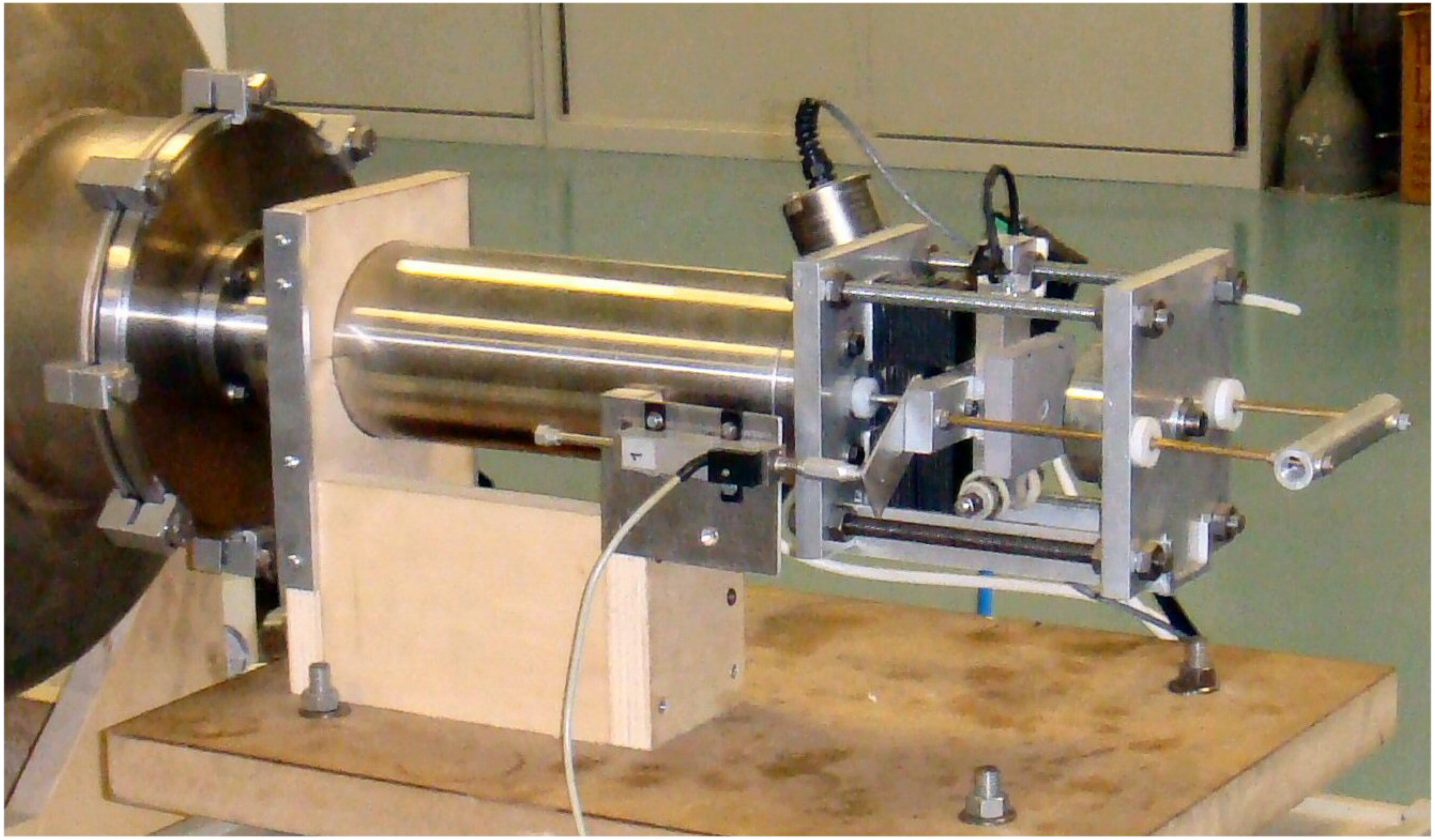


Working principle of the annular piston:

System timing

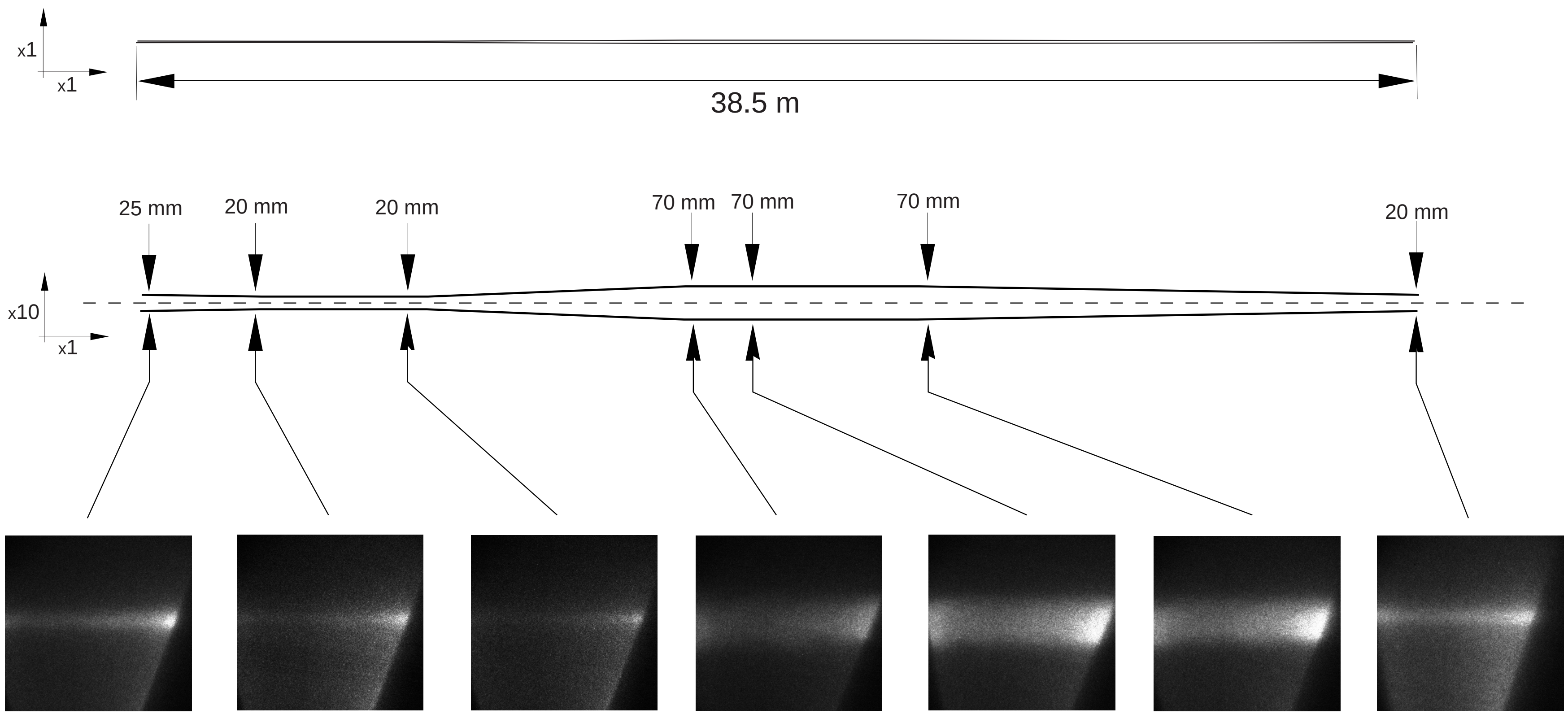


Piston view (connected to the vacuum vessel):



Camera / triggered intensifier view

Working tests: a M=15 Argon jet



10 Bibliography

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